Astrophysical Gamma Ray Emission Lines[1]

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ABSTRACT

We review the wide range of astrophysical observations of gamma ray emission lines and we discuss their implications. We consider line emission from solar flares, the Orion molecular cloud complex, supernovae 1987A and 1991T, the supernova remnants Cas A and Vela, the interstellar medium, the Galactic center region and several Galactic black hole candidates. The observations have important, and often unique, implications on particle acceleration, star formation, processes of nucleosynthesis, Galactic evolution and compact object physics.

1. INTRODUCTION

Gamma ray lines are the signatures of nuclear and other high energy processes occurring in a wide variety of astrophysical sites, ranging from solar flares and the interstellar medium to accreting black holes and supernova explosions. Their measurement and study provide direct, and often unique, information on many important problems in astrophysics, including particle acceleration, star formation, nucleosynthesis and the physics of compact objects.

The physical processes that produce astrophysical gamma ray emission lines are nuclear deexcitation, positron annihilation and neutron capture. Excited nuclear levels can be populated by the decay of long-lived radioactive nuclei as well as directly in interactions of accelerated particles with ambient gas. Nuclear deexcitation lines following radioactive decay have been seen from supernova 1987A (Matz et al. 1988; Tueller et al. 1990; Kurfess et al. 1992), from the supernova remnants Cas A (Iyudin et al. 1994) and Vela (Diehl et al. 1995), and the interstellar medium (Mahoney et al. 1984; Share et al. 1985; Diehl et al. 1994; 1995). The observation of such line emission provides unique information on processes of nucleosynthesis. Nuclear deexcitation lines following accelerated particle interactions have been observed from solar flares (Chupp et al. 1973; Rieger 1989; Chupp

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1990) and recently from the Orion molecular cloud complex with the COMPTEL imaging spectrometer on the Compton Gamma Ray Observatory (CGRO, Bloemen et al. 1994). The observed Orion lines, at 4.44 MeV from ^{12}C and 6.13 MeV from ^{16}O, cannot result from processes of nucleosynthesis since there are no significant long lived radioactive isotopes that decay into the excited states of these nuclei. The lines must therefore be produced contemporaneously by accelerated particles.

The accelerated ions which produce the deexcitation lines also produce neutrons and positrons. The neutrons can be captured by various nuclei. Capture on hydrogen produces deuterium and 2.223 MeV line photons. This line has been extensively observed from solar flares (e.g. Chupp 1990). Capture on ^{56}Fe produces ^{57}Fe and a variety of gamma ray lines, the most important of which are at 7.645 and 7.631 MeV corresponding to captures into the ground state and first excited state of ^{57}Fe. The observability of the neutron capture lines requires a region in which the ambient density is high enough to allow the capture of the neutrons before they decay and the opacity low enough to allow the escape of the line emission. Such a site is provided by the solar photosphere. Neutron capture lines have not yet been seen from other astrophysical sites, except for unconfirmed lines from a transient source (Ling et al. 1982) which were interpreted as redshifted lines from neutron capture on both hydrogen and iron (Lingenfelter, Higdon, and Ramaty 1978).

Positron-electron annihilation leads to the 0.511 MeV line provided that the temperature of the annihilation site is sufficiently low; otherwise the annihilation radiation is broadened and blueshifted, and at temperatures approaching $m_e c^2/k$ it is eventually smeared into a continuum. The annihilation radiation can also be redshifted, leading to line emission below 0.511 MeV, if the annihilation site is sufficiently close to a neutron star or black hole. A narrow line at precisely 0.511 MeV (with line centroid error of only a few tenths of keV and width less than 3 keV) has been observed on many occasions with Ge detectors from the direction of the Galactic center (Leventhal, MacCallum, and Stang 1978; Gehrels et al. 1991; Smith et al. 1993). This line has also been observed with the OSSE instrument on CGRO (Purcell et al. 1993). The line centroid and width require that the positrons annihilate in the interstellar medium, at considerable distances from compact objects.

Line features at energies just below 0.511 MeV have been seen from Galactic black hole candidates (e.g. Gilfanov et al. 1994; Smith et al. 1993; Briggs et al. 1995). Their origin, however, is not clear. They have generally been attributed to redshifted annihilation radiation, although they could also be due to the Compton down scattering of collimated high energy continuum (Skibo, Dermer, and Ramaty 1994). Another line produced by Compton scattering is that at $\sim$0.2 MeV. This line, seen from the black hole candidate Nova Muscae (Goldwurm et al. 1992; Sunyaev et al. 1992) and unidentified objects in the direction of the Galactic center (Leventhal and MacCallum 1980, Smith et al. 1993), has been identified with Compton backscattered annihilation radiation (Lingenfelter and Hua 1991). However, the feature could also result from Compton down scattering of higher energy continuum in a jet (Skibo et al. 1994).

Cyclotron absorption features in intense (teragauss) magnetic fields have been observed from X-ray binaries and gamma ray bursts. As here we deal only with emission

lines, we shall not discuss these features. Instead, we refer the reader to our previous review (Ramaty and Lingenfelter 1994).

The plan of the present article is as follows: in section §2 we deal with the line emission from accelerated particle interactions and we discuss solar flares and Orion; in §3 we treat the lines from processes of nucleosynthesis and we discuss the supernova and ^{26}Al observations; in §4 we deal with Galactic positron annihilation; in §5 we discuss gamma ray line emissions from black hole candidates; and we present our conclusions in §6.

2. ACCELERATED PARTICLE INTERACTIONS

The interactions of accelerated particles with ambient matter produce a variety of gamma ray lines following the deexcitation of excited nuclei in both the ambient matter and the accelerated particles. Deexcitation gamma ray lines can be broad, narrow or very narrow, depending on their widths. Broad lines are produced by accelerated C and heavier nuclei interacting with ambient H and He. The broadening of these lines (widths ranging from a few hundreds of keV to an MeV) is due to the motion of the accelerated heavy particles themselves. Narrow lines are produced by accelerated protons and α particles interacting with ambient He and heavier nuclei. The broadening in this case (widths ranging from a few tens of keV to around 100 keV), is due to the motion of the heavy targets which recoil with velocities much lower than those of the projectiles. The ^{7}Li and ^{7}Be deexcitation lines at 0.478 and 0.429 MeV, produced by α particle interactions with ambient He, are also considered as narrow. Very narrow lines result from excited nuclei which have slowed down and stopped due to energy losses before emitting gamma rays. The broadening of these lines is due only to the bulk motion of the ambient medium (widths around a few keV or less for the interstellar medium).

There are two distinct processes which can lead to very narrow line emission: deexcitation of heavy nuclei embedded in dust grains (Lingenfelter and Ramaty 1976), and deexcitation of excited nuclei populated by long lived radionuclei. In the case of the dust, the excitations are due to protons and α particles. The best example of a very narrow grain line is that at 6.129 MeV from ^{16}O. The mean life of the corresponding nuclear level, 1.2×10^{-11} s, is long enough to allow the excited nucleus to stop in grain material before the gamma ray is emitted. In contrast, the 4.438 MeV line of ^{12}C cannot be very narrow because the lifetime of the corresponding level, 2.9×10^{-14} s, is too short to allow the excited nucleus to stop. In addition to a relatively long lifetime, the production of very narrow grain lines also requires grains that are large enough. Their size distribution and the amount of O locked up in dust will then determine the ratio of the very narrow to narrow 6.129 MeV line fluxes. A ratio of about 1/3 is a reasonable average.

Long lived radionuclei produced by accelerated particle bombardment can stop in ambient gas before they decay thereby producing excited nuclei essentially at rest. The most important such radionuclei are ^{55}Co($\tau_{1/2} = 17.5$h), ^{52}Mn($\tau_{1/2} = 5.7$d), ^{7}Be($\tau_{1/2} = 53.3$d), ^{56}Co($\tau_{1/2} = 78.8$d), ^{54}Mn($\tau_{1/2} = 312$d), ^{22}Na($\tau_{1/2} = 2.6$y), and ^{26}Al($\tau_{1/2} = 0.72$my), all of which can be produced in accelerated particle interactions, for example ^{56}Fe(p,n)^{56}Co. Unlike the very narrow grain lines which are produced almost exclusively by accelerated protons and α particles, very narrow lines from long lived radioactivity can result from both these interactions and interactions due to accelerated heavy nuclei. When

the interactions are predominantly due to heavy ion interactions (as might be the case for Orion, see below), the only narrow features in the spectrum are those from the long lived radioisotopes. To produce a very narrow 0.847 MeV line from ^{56}Co it is necessary to stop a $\sim$10 MeV/nucleon ^{56}Co in less than about 100 days, and this requires that the density of the ambient medium exceed about 2×10^4 cm^{-3}. Such densities may be present in dense molecular clouds. Clearly the discovery of very narrow lines would provide unique information on the density of the medium in which the lines are formed.

A theoretical spectrum, (Fig. 1 from Ramaty 1995) illustrates some of the above line features. The calculated spectra were obtained by using a nuclear deexcitation line code which employs a large number of nuclear reaction cross sections and allows calculations to be performed for a variety of compositions, accelerated particle spectra and interaction models (Ramaty, Kozlovsky, and Lingenfelter 1979; Murphy et al. 1991). The top panel of Fig. 1 shows a deexcitation line spectrum obtained by assuming a solar photospheric composition for the ambient medium and cosmic ray source composition for the accelerated particles. Both broad and narrow lines, as well as very narrow lines from long lived radionuclei, are present. (Very narrow lines from dust, however, are not included). The ^{12}C complex around 4.44 MeV clearly shows the narrow line superimposed on its broad counterpart. The bottom panel of the figure shows the spectrum obtained by suppressing the accelerated protons and α particles. The narrow lines are obviously absent in this case. However, we now can clearly see the very narrow lines from the long lived radionuclei. To allow the shortest lived radionucleus to stop before it decays, we assumed that the ambient density exceeds 2×10^6 cm^{-3}.

As mentioned in the Introduction, gamma ray lines from accelerated particle interactions were seen from the flaring Sun and the Orion Complex. We first consider the flares.

2.1 Solar Flares

Gamma ray lines from solar flares were first observed in 1972 with the NaI scintillator on OSO-7 (Chupp et al. 1973). But it was not until 1980 that routine observations of gamma ray lines and continuum became possible with the much more sensitive NaI spectrometer on the Solar Maximum Mission (SMM, Rieger 1989; Chupp 1990). The SMM detector operated successfully until 1989, making important observations during both the declining portion of solar cycle 21 (1980-1984) and the rising portion of cycle 22 (1988-1989). Additional gamma ray line observations during cycle 21 were carried out with a CsI spectrometer on HINOTORI (Yoshimori 1990). During the peak of solar cycle 22 solar flare gamma ray line observations were carried out with the CGRO instruments OSSE (Murphy et al. 1993), COMPTEL (Ryan et al. 1993), and EGRET (Schneid et al. 1994, see also Ramaty et al. 1994), with the Phebus instrument on GRANAT (Barat et al. 1994), and with a gamma ray spectrometer on YOHKOH (Yoshimori et al. 1994).

A theoretical solar flare gamma ray spectrum is shown in Fig. 2, calculated for interactions of flare accelerated ions and electrons having power law energy spectra with an index of -3.5; the calculated spectra are normalized to the observed 4–7 MeV gamma ray flux in the flare of 27 April 1981. These are the same parameters as those used in our previous review (Ramaty and Lingenfelter 1994), except that here we have limited

the range of photon energies to 0.1 – 10 MeV. The strongest line, at 2.223 MeV from neutron capture, is discussed separately below. The narrow deexcitation lines at 6.129 MeV from ^{16}O, 4.438 MeV from ^{12}C, 1.779 MeV from ^{28}Si, 1.634 MeV from ^{20}Ne, 1.369 MeV from ^{24}Mg, and 0.847 MeV from ^{56}Fe are clearly seen. The corresponding broad deexcitation lines, together with a variety of other unresolved lines, form the excess above the bremsstrahlung continuum represented by the dashed curve. The line at 0.511 MeV is from positron annihilation, and the excess continuum just below 0.511 MeV is due to positronium annihilation. The strength of this continuum relative to the 0.511 MeV line depends primarily on the density of the ambient gas. These calculations are for a positronium fraction of 0.9, which requires that the positrons annihilate in a region of density lower than about 10^{15} cm^{-3} (Crannell et al. 1976). Since we assumed an isotropic distribution of interacting particles the ^{7}Li and ^{7}Be deexcitation lines at 0.478 MeV and 0.429 MeV (Kozlovsky and Ramaty 1974) blend into a single feature which peaks at $\sim$0.45 MeV, as can be seen in the insert in Fig. 2. However, under certain conditions of anisotropy, this feature breaks up into two individual lines (Kozlovsky and Ramaty 1977).

As already mentioned, the 2.223 MeV line is formed by neutron capture on ^{1}H in the photosphere, at a much larger depth than that at which the nuclear reactions take place. Consequently, the ratio of the 2.223 MeV line fluence to the fluence in the deexcitation lines depends on the position of the flare on the solar disk (Wang and Ramaty 1974; Hua and Lingenfelter 1987). The ratio becomes quite small for flares at or near the limb, and can vanish for flares behind the limb. This was demonstrated most dramatically by gamma ray observations of a flare on 1 June 1991 located at 10° degrees behind the limb for which the 2.223 MeV line was absent while the deexcitation lines were still seen (Barat et al. 1994). Evidently, a considerable fraction of the nuclear reaction occurred in the corona, at a site which was visible even though the location of the optical flare was occulted. While this 'classical' behavior is reassuring, (that the 2.223 MeV should be formed in the photosphere and hence strongly attenuated from flares located at or behind the limb was predicted theoretically, Wang and Ramaty 1974), there is another observation of a flare about 10 ± 5 degrees behind the limb for which only the 2.223 MeV line was seen (Vestrand and Forrest 1993). This flare, on 29 September 1989, was one of the largest on record, having produced a multitude of emissions including protons up to 25 GeV (Swinson and Shea 1990). Because of the very strong expected attenuation, the observed 2.223 MeV line must have been produced by charged particles interacting on the visible hemisphere of the Sun. It was suggested (Cliver, Kahler and Vestrand 1993) that these particles were accelerated by a coronal shock over a large volume thereby producing an extended gamma ray emitting region visible from the Earth even if the optical flare was behind the limb.

The ratio of the fluence of the bremsstrahlung continuum to that in the lines was used to determine the electron-to-proton ratio (e/p) for the accelerated particles which interact at the Sun (Ramaty et al. 1993). The derived values of e/p were found to be generally larger than the corresponding e/p's obtained from observations of solar flare particle events in interplanetary space. Such interplanetary e/p observations have been used to distinguish two classes of solar flare particle events (Cane, McGuire and von Rosenvinge 1986; Reames 1990). Impulsive events, for which the associated soft X-ray emission is of relatively short duration, have large e/p ratios; gradual events, for which the soft X-rays last longer, exhibit

smaller values of e/p. The gamma ray results reveal comparable or even higher values of e/p than the impulsive events in space, regardless of whether the flare is impulsive or gradual. This result suggests that the particles which are trapped at the Sun and produce the gamma rays, and the particles observed in interplanetary space from impulsive flares are accelerated by the same mechanism, probably stochastic acceleration due to gyroresonant interactions with plasma turbulence. Relativistic electron acceleration by such turbulence, particularly whistler waves, can be quite efficient (Miller and Steinacker 1992). On the other hand, for gradual events the particles are thought to be accelerated from cooler coronal gas probably by a shock which is not expected to accelerate electrons efficiently.

In Fig. 3 we show a solar flare gamma ray spectrum observed with the NaI spectrometer on SMM (Murphy et al. 1990). The ^{16}O, ^{12}C and ^{20}Ne lines can be clearly seen, but the ^{24}Mg line is not resolved from several neighboring features (compare with Fig. 1). The annihilation line, possibly accompanied by a positronium continuum, and the α–α lines produce a broad feature above the strong bremsstrahlung continuum. The 2.223 MeV line is weak because of the location of this flare at the limb of the Sun.

The spectrum shown in Fig. 3 was used to determine abundances in both the ambient solar atmosphere and the accelerated particle population (Murphy et al. 1991). For the accelerated particles the results indicate that the abundances of the heavy elements, in particular Mg and Fe, are significantly enhanced (relative to C and O) in comparison to their abundances in either the photosphere or the corona. Similar enhancements are observed in the abundances of the accelerated particles observed from impulsive flares (Reames 1990). This supports the conclusion mentioned above that the particles responsible for gamma ray production and the particles observed in interplanetary space from impulsive flares are accelerated by the same mechanism. It has been shown (Miller and Viñas 1993) that stochastic acceleration by plasma turbulence produce these enhancements (Reames, Meyer and von Rosenvinge 1994).

For the ambient gas, the Mg, Si and Fe abundances relative to C and O are consistent with coronal abundances but enhanced in comparison with photospheric abundances. The enhanced Mg, Si and Fe abundances (elements with low first ionization potential, FIP) could be understood in terms of a charge dependent ambient gas transport process from the photosphere to the chromosphere and corona which favors the collisionally ionized, low FIP elements in the photosphere (Meyer 1985). Indeed, the enhancement of the low FIP elements in the corona is rather well established from various observations, in particular solar flare accelerated particle observations. The abundance of Ne determined from the gamma ray data is problematic. Based primarily on the strong 1.634 MeV ^{20}Ne line (Fig. 2), the gamma ray data yielded (Murphy et al. 1991) a Ne to O ratio that is more than a factor of 2 larger than the coronal Ne/O which is thought to be consistent with the local galactic Ne abundance (Meyer 1989). The photospheric Ne abundance is not known, so in principle it is possible that the gamma ray derived abundance would be representative of the photosphere. This point of view, however, is challenged by other astronomical data which would favor a photospheric Ne abundance about equal to its coronal value (Meyer 1989). It has been proposed that the Ne enhancement could be due to photoionization by soft X-rays (Shemi 1991), an interpretation which predicts that S should also be enhanced. Both the Ne and S enhancements have been confirmed by soft

X-ray observations (Schmelz 1993), but only in one flare. Thus the issue of the gamma ray derived Ne abundance remains unresolved, awaiting new observations and their analysis.

Another isotope whose photospheric abundance is not well known is ^{3}He. It was first pointed out by Wang and Ramaty (1974) that ^{3}He in the photosphere could capture as much as one half of the neutrons, so that the flux and time profile of the 2.223 MeV line, resulting from the capture of the other half on ^{1}H, would strongly depend on the photospheric ^{3}He abundance. Observations (Prince et al. 1983) of the time dependent flux of the 2.223 MeV line were used (Hua and Lingenfelter 1987) to derive a photospheric $^3\mathrm{He/H} \simeq 2 \times 10^{-5}$, which is sufficiently low to be consistent with the ^{3}He abundance expected solely from primordial nucleosynthesis without requiring much mixing in the solar atmosphere.

Thus, we see that gamma ray emission lines from the Sun are providing a wealth of new information on both abundances and the acceleration of energetic particles in the solar flares.

2.2 The Orion Complex

The recent discovery of gamma ray emission lines from the Orion giant molecular cloud complex has now revealed exciting new particle acceleration processes in this nearest region of recent star formation that have very important implications for light element nucleosynthesis. Gamma ray line emission in the 3 to 7 MeV range was observed from the Orion complex (Fig. 4a) with COMPTEL (Bloemen et al. 1994). The radiation shows (Fig. 4b) emission peaks near 4.44 and 6.13 MeV, consistent with the deexcitation of excited states in ^{12}C and ^{16}O produced by accelerated particle interactions. Moreover, the intensity of these lines is roughly two orders of magnitude greater than that expected from irradiation by low energy cosmic rays with energy density equal to that of the local Galactic cosmic rays (Ramaty et al. 1979). Thus this emission requires that the ambient matter in Orion, both gas and dust, is undergoing bombardment by an unexpectedly intense, locally accelerated, population of energetic particles.

Implication of Gamma Ray Emission Lines

We have explored (Ramaty, Kozlovsky and Lingenfelter 1995a,b) the implications of these observations on the composition, energy spectra and total power of the accelerated particles in the Orion region. As we will discuss in detail, we have found that the ratio of the measured flux in the 3 to 7 MeV band compared to limits on the 1 to 3 MeV band place very strong constraints on the composition of the accelerated particles, requiring significant enrichment in C and O relative to the heavier elements in order not to produce too much line emission in the 1 to 3 MeV band. At the same time, the overall energetics and efficiency of the gamma ray line production require significant enrichment of C and O relative to H and He. The lack of enhanced flux at higher (>100 MeV) energies also requires that the accelerated particles have a much softer energy spectrum than that of the Galactic cosmic rays. But the spectrum of the accelerated particles should not be too soft in order to maintain an acceptable overall energetic efficiency.

We have calculated the gamma ray line emission rate together with the power deposited by the accelerated particles during gamma ray production. In the thick target

model which we employ, the ratio of the photon production rate to the power deposited by the accelerated particles depends only on the composition and spectrum of the accelerated particles and on the composition and state of ionization of the ambient medium. In Fig. 5 (from Ramaty et al. 1995b) we show the deposited power at Orion for a neutral ambient medium with solar system abundances and for various accelerated particle compositions as a function of the spectral parameter E_0 of the accelerated particles. The spectrum

$$N_i(E) = K_i E^{-1.5} e^{-E/E_0}, \tag{1}$$

where E is energy per nucleon and the K_i's are proportional to the assumed abundances, is predicted by acceleration to nonrelativistic energies near a strong shock (compression ratio $r = 4$) with the effects of a finite acceleration time or a finite shock size taken into account by the exponential turnover (e.g. Ellison and Ramaty 1985). We have carried out calculations for E_0 in the range 2–100 MeV/nucl; E_0, however, should not exceed about 30 MeV/nucl, because otherwise the accelerated particles would contribute to pion production and thus be in conflict with the high energy gamma rays observed from Orion with EGRET; these data only require a cosmic ray flux equal to that observed locally near Earth (Digel, Hunter and Mukherjee 1995).

The curves in Fig. 5 correspond to various assumed accelerated particle compositions (Ramaty et al. 1995b): SS – solar system (Anders and Grevesse 1989), CRS – cosmic ray source (Mewaldt 1983), SN35 – the ejecta of a 35 M$\odot$ supernova (Weaver and Woosley 1993), WC – the late phase wind of a Wolf-Rayet star of spectral type WC (Maeder and Meynet 1987); GR – pick up ions resulting from the breakup of interstellar dust. Concerning the dust, in analogy with the anomalous component of the cosmic rays observed in interplanetary space (e.g. Adams et al. 1991), we considered the effects of the pick up of ions onto a magnetized high speed wind (e.g. the ejecta of supernovae or the winds of massive stars). As the ions acquire considerable energy during the pick up process, they form a seed population that is much more easily accelerated than the rest of the ambient plasma. In the solar system the pick up ions are interstellar neutrals that penetrate into the solar cavity where they are ionized. For Orion we proposed that the incoming matter is essentially neutral dust that is broken up by evaporation, sputtering or other processes. The GR composition, therefore, has no He and Ne and is relatively poor in H. The SS and CRS compositions will thus produce combined broad and narrow line spectra, while the WC and GR compositions will lead to essentially pure broad line spectra. The SN35 will still have a weak narrow line component. We see from In Fig. 5 that the gamma ray line production is energetically most efficient for large values of E_0 and accelerated particle compositions that are poor in protons and α particles (i.e. the GR and WC compositions). Thus, just from energetic arguments, the broad line spectra are preferred, even though the COMPTEL gamma ray data can so far not distinguish between pure broad line spectra and combined broad and narrow line spectra (i.e. spectra produced by heavy projectiles as well as protons and α particles, Ramaty et al. 1995a).

For the GR and WC compositions and E_0 = 30 MeV/nucl, the deposited power is 4x10^{38} erg s^{-1} and the ionization rate is 0.3 $M_\odot$ yr^{-1} or $\zeta = 10^{-13}$ M_5^{-1} (H atom)$^{-1}$ s^{-1},

where M_5 is the total irradiated neutral H mass in units of 10^5 solar masses. Setting the ionization rate equal to the recombination rate,

$$\zeta n_{\rm H} = \alpha_r n_{\rm e} n_{\rm H}, \tag{2}$$

where $\alpha_r \simeq 10^{-11}(T/100{\rm K})^{-0.7}$ (Bates and Dalgarno 1962), we obtain an equilibrium electron density $n_{\rm e} = 0.01\ M_5^{-1}\ (T/100{\rm K})^{0.7}$. We thus see that, even though the rate of ionization is quite high, for a large enough irradiated mass and temperature typical of dense molecular clouds, the irradiated cloud can remain essentially neutral. The total deposited power depends of course on the duration of the irradiation. For example, if the accelerated particle bombardment lasts $\sim 10^5$ years, the total energy requirement would be 1.2x10^{51} ergs, equal to the total mechanical output a supernova.

Just such a supernova, occurring $\sim$ 80,000 years ago in the OB association at $l = 208°$ and $b = -18°$, the same location as the center of the gamma ray line source, was suggested by Burrows et al. (1991) from analyses of the X-ray emission from the Orion-Eridanus bubble.

In addition to being energetically efficient, the WC and GR compositions have the advantage of predicting gamma ray spectra which are consistent with the upper limit set by the COMPTEL observations on the emission in the 1–3 MeV range. We have shown (Ramaty et al. 1995b) that the discrepancy between this limit and the CRS prediction is greater than 3σ, and that the predictions of the SS and SN35 compositions are also inconsistent at greater than 2σ. On the other hand, both the GR and WC compositions yielded 1–3 MeV fluxes which are lower than the COMPTEL upper limit. However, while the WC composition predicts practically no emission in the 1–3 MeV region, the GR composition predicts significant broad line emission in this region, due to Mg, Si and Fe. The reduction in the overall 1–3 MeV emission for the GR case is caused by the absence of 1.634 MeV line due to the lack of Ne in grains.

The nature of the acceleration mechanism in Orion is still very poorly understood. Acceleration by the shocks associated with the winds of young O and B stars was proposed by Nath and Biermann (1994), while Bykov and Bloemen (1994) proposed that the acceleration is due to the shocks produced by colliding stellar winds and supernova explosions. We have proposed (Ramaty et al. 1995b) that the pick up ions resulting from the breakup of interstellar grains could be the dominant injection process to any of these acceleration mechanisms. We have also emphasized the comparison with solar flares (Ramaty 1995; Ramaty et al. 1995a). The solar flare gamma ray spectra show much higher ratios of 1–3 MeV to 3–7 MeV fluxes than does Orion. It was shown (Murphy et al. 1991) that this enhanced emission below 3 MeV is, in part, due to the enrichment of the flare accelerated particle population in heavy nuclei. Such enrichments are routinely seen in direct observations of solar energetic particles from impulsive flares (e.g. Reames, Meyer and von Rosenvinge 1994). These impulsive flare events are also rich in relativistic electrons. On the other hand, in gradual events the composition is coronal and the electron-to-proton ratio is low. As we have pointed out above, the acceleration in impulsive events is thought to be due to gyroresonant interactions with plasma turbulence while in gradual events it is the result of shock acceleration. The fact that the ratio of bremsstrahlung-to-nuclear line emission in Orion is very low lends support to the shock acceleration scenario. Moreover,

as we noted above, these shocks may be powered by an $\sim$ 80,000 year old supernova of a massive star in the OB association which is also responsible for the Orion-Eridanus bubble.

The Relationship to Light Isotope Production

That cosmic ray spallation is important to the origin of the light isotopes ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B has been known for over two decades (Reeves, Fowler and Hoyle 1970). It was shown that cosmic rays with flux equal to the observed flux near Earth, interacting with interstellar matter prior to the formation of the solar system, can produce the observed solar system abundances of ^{6}Li, ^{9}Be and ^{10}B (Meneguzzi, Audouze and Reeves 1971; Mitler 1972). Since low energy cosmic rays with spectra similar to that of the accelerated particles in Orion also produce these isotopes, the Galactic inventories of ^{6}Li, ^{9}Be and ^{10}B can set limits on the total Galactic irradiation by such low energy cosmic rays. In Fig. 6 (from Ramaty et al. 1995b) we show the ratio of ^{9}Be production to 3–7 MeV deexcitation photon production. As both the 3–7 MeV photons and the ^{9}Be are produced predominantly in interactions involving C and O, this ratio is practically independent of composition. Adopting a total Galactic ^{9}Be inventory of 10^{57} atoms and assuming that currently there are N_{orr} regions in the Galaxy with the same level of low energy cosmic ray activity as Orion (i.e. producing 3–7 MeV nuclear gamma rays at a rate $Q_{orr}(3-7\text{MeV})$ $= 2.3\text{x}10^{39}$ s^{-1}), we have that

$$N_{orr}Q_{orr}(3-7\text{MeV})\big[Q(^9Be)/Q(3-7)\text{MeV}\big]T_{irr} < 10^{57}\text{atoms}, \qquad (3)$$

where the quantity in square brackets is from Fig. 6 and T_{irr} is the total duration of the irradiation. Taking $Q(^9Be)/Q(3-7\text{MeV}) = 8\times10^{-3}$ (from Fig. 6) and $T_{irr} = 3\times10^{17}$ s, the Galactic age, we get that $N_{orr} < 200$. Eq. (3) assumes the irradiation is constant in time and ignores the destruction of ^{9}Be in stars. Using a similar argument, but employing the Galactic inventory of B, Reeves and Prantzos (1995) obtained $N_{orr} < 100$. They obtained a lower value because the B inventory of 10^{58} atoms that they used corresponds (for the solar system B/Be) to a ^{9}Be inventory which is lower by a factor of 3 than the value we used.

The upper limit on the number of currently active 'Orion-like' regions can be used to set limits on the 3–7 MeV nuclear line emission from the central regions of the Galaxy. For a given type of emission (e.g. the 3–7MeV nuclear line emission), the relationship between the flux from the solid angle defined by the central radian of Galactic longitudes and all latitudes, Φ_{crad}, and the total Galactic photon luminosity, Q_G, can be written as

$$\Phi_{\text{crad}}(3-7\text{MeV}) = \xi 10^{-46}Q_G(3-7\text{MeV}) = \xi 10^{-46}N_{orr}Q_{orr}(3-7\text{MeV}), \qquad (4)$$

where ξ is obtained by integrating the photon source distribution along all the lines of sight within the above solid angle. For a variety of assumed Galactic source distributions ξ was found to range from about 0.6 to 1.7 (Skibo 1993). Thus, for $N_{orr} < 200$, Φ_{crad}(3–7MeV) $< 5\text{x}10^{-5}\xi$ photons cm^{-2} s^{-1}, which is lower by at least a factor of 3 than the upper limit on Φ_{crad}(3–7MeV) obtained from SMM data (Harris, Share and Messina 1995). We note, however, that the limit on N_{orr} obtained from ^{9}Be would become higher if a significant amount of ^{9}Be is destroyed by incorporation into stars. On the other hand, the limit would

be lower if the rate of irradiation in the early Galaxy was much higher than the average. We clearly need more observations of nuclear gamma ray lines to map out the distribution of low energy cosmic rays in the Galaxy.

While Galactic cosmic ray spallation can account for the ^{6}Li, ^{9}Be and ^{10}B, such cosmic rays cannot account for the abundances of ^{7}Li and ^{11}B. The ^{11}B excess is probably produced by spallation, either by low energy cosmic rays (Casse, Lehoucq and Vangioni-Flam 1995) or by neutrinos in supernovae (Woosley et al. 1990). Here we discuss some of the issues related to Li.

^{7}Li production in standard big bang nucleosynthesis models leads to $^7\mathrm{Li}/^1\mathrm{H} \sim 10^{-10}$, in agreement with the ^{7}Li abundance in extremely metal deficient Pop II stars (see Reeves 1994 and references therein). This cosmological ^{7}Li, however, is insufficient to account for the ^{7}Li abundance in Pop I stars and meteorites, where $^7\mathrm{Li}/^1\mathrm{H} \sim 10^{-9}$. The excess ^{7}Li is thought to be produced in stars, most likely AGB stars, although neutrino induced spallation in supernovae was also considered (Woosley et al. 1990). Thus, while cosmic ray spallation leads to $^7\mathrm{Li}/^6\mathrm{Li} \simeq 1.4$ (Reeves 1994), the enhanced meteoritic $^7\mathrm{Li}/^6\mathrm{Li}$ of 12.3 is generally understood as being due to these additional ^{7}Li sources. That the enhancement cannot be due to low energy cosmic rays with spectrum given by eq.(1) can be seen from Fig. 7, which shows our calculations of $^7\mathrm{Li}/^6\mathrm{Li}$ as a function of E_0 for the 5 assumed compositions. For E_0 around 30 MeV/nucl, $^7\mathrm{Li}/^6\mathrm{Li}$ is 1.5 independent of composition and essentially equal to the cosmic rays ratio.

Rather than producing the high meteoritic $^7\mathrm{Li}/^6\mathrm{Li}$, strong localized irradiation by low energy cosmic rays could significantly lower this ratio in selected molecular clouds that have undergone 'Orion-type' irradiation episodes (Lemoine, Ferlet and Vidal–Madjar 1995; Reeves and Prantzos 1995). This argument is suggested by the recent observations of Lemoine et al. (1995) which indicate that in the direction of ζ Oph there are two absorbing clouds (A and B) with different Li isotopic ratios, $(^7\mathrm{Li}/^6\mathrm{Li})_A \simeq 8.6$ and $(^7\mathrm{Li}/^6\mathrm{Li})_B \simeq 1.4$. However, the energetic and ionization implications of the required massive low energy cosmic ray irradiation have not yet been examined.

The Relationship to ^{26}Al Production

Evidence for the existence of freshly nucleosynthesized ^{26}Al in the interstellar medium is provided by the observations of the 1.809 MeV line from various directions in the Galaxy, as we discuss in detail below (see §3.3). Evidence for the presence of live ^{26}Al at the time of the formation of the solar system was obtained from the analysis of meteoritic material (Lee, Papanastassiou and Wasserburg 1977). Motivated by the Orion gamma ray line observations, Clayton (1994) suggested that both the general Galactic ^{26}Al and the protosolar ^{26}Al could result from low energy cosmic ray spallation. However, the production ratio of ^{26}Al to 3–7 MeV line emission from such spallation reactions, $< 10^{-2}$ (Ramaty et al. 1995a), combined with the upper limit on the Galactic 3–7 MeV line flux set by the SMM data (Harris et al. 1995), shows that low energy cosmic rays produce at best only 1% of the total Galactic ^{26}Al.

Although Clayton and Jin (1995) now recognize that it is not possible to produce the Galactic ^{26}Al by spallation, they still argue that the protosolar ^{26}Al could have resulted from an episode of low energy cosmic ray irradiation similar to that currently taking place in Orion. We have shown (Ramaty et al. 1995a), however, that the COMPTEL

Orion observations, and in particular the upper limit on the 1–3 MeV emission, imply a significantly lower ^{26}Al production rate than that estimated by Clayton (1994) to suggest that the protosolar ^{26}Al/^{27}Al of 5x10^{-5} could have resulted from low energy cosmic ray bombardment. That argument, however, depended on the total irradiated mass and on the level of protosolar low energy cosmic ray activity which could have been different from that in Orion.

More recently by comparing the ^{9}Be and ^{26}Al yields, we have shown (Ramaty et al. 1995b) that an independent limit can be set on possible protosolar spallation production of ^{26}Al that does not depend of these parameters. In Fig. 8 we show the ratio of ^{26}Al to ^{9}Be production. The solid bar is the ratio implied by the protosolar value of ^{26}Al/^{27}Al and the SS ^{27}Al/^{9}Be. We see that for $E_0 > 10$ MeV/nucl (lower values are energetically very inefficient) the SS ^{9}Be abundance limits the contribution of particle bombardment to ^{26}Al/^{27}Al to less than 3 to 10% for compositions consistent with the 1–3 MeV flux limits. Moreover, if we take into account the facts that most of the ^{9}Be had already been produced prior to the formation of the protosolar nebula, and that some of the ^{26}Al must have decayed during irradiation, these limits become much lower. This shows that it is practically impossible to produce the protosolar ^{26}Al by accelerated particle bombardment, quite independent of the amount of material irradiated.

3. GAMMA RAY LINES FROM NUCLEOSYNTHESIS

Because the sites of explosive nucleosynthesis are optically thick to gamma-rays, only the delayed gamma ray line emission from the decay of synthesized radionuclei can be observed from such sites that become at least partially transparent on time scales less than the radioactive decay mean lives. Such gamma ray lines from the decay of ^{56}Co and other freshly synthesized radionuclei in supernovae were predicted by Clayton, Colgate and Fishman (1969). The most intense lines are from ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe decay, followed by those from ^{57}Co$\rightarrow^{57}$Fe and ^{44}Ti$\rightarrow^{44}$Sc $\rightarrow^{44}$Ca. Such radionuclei, carried outward in the expanding supernova envelope, decay and then deexcite by gamma ray line emission. At early times, the gamma rays interact with the material in the supernova and are Compton scattered down to X-ray energies which are photoelectrically absorbed and their energy is eventually released at longer wavelengths. However, as the supernova expands, some of the gamma rays begin to escape without scattering. These gamma ray lines are Doppler-broadened by the velocity spread of the radionuclei in the expanding nebula. The gamma ray line shapes therefore reflect the velocity distribution within the supernova, modified by the opacity along the line of sight, and their measurement with high resolution spectrometers can give us information on this distribution.

Thus, observations of these gamma ray lines provide the most direct means of testing current models of both explosive nucleosynthesis and the dynamics of supernova ejecta. These gamma ray lines, coming directly from the decay of radioactive nuclei freshly produced in supernova explosions, give a straight forward measure of the nucleosynthetic yields of the supernovae. Being nuclear lines, their emission rates are directly determined from their known branching ratios and radioactive half lives; they are not subject to the uncertainties in the estimated excitation rates that complicate the interpretation of atomic lines. Moreover, because of Doppler broadening and Compton attenuation, a wealth of

information about the mass-velocity distribution of the ejecta, and the distribution of nucleosynthetic products within it, can be obtained (Clayton 1974, Chan and Lingenfelter 1987; 1988; 1991; Gehrels, Leventhal and MacCallum 1987; Ruiz-Lapuente et al. 1993) from the time dependent observations of the intensity ratios and spectral shapes of the gamma ray lines.

Type Ia supernovae, which are thought to occur in accreting white dwarfs and are optically defined by their lack of hydrogen envelopes, are the most luminous sources of such lines, because the bulk of the star is explosively burned to produce nearly $1M_\odot$ of ^{56}Ni, leaving a relatively small ($< 1M_\odot$) overlying envelope to obscure the emission. On the other hand, the other Type I and the Type II supernovae, which are optically defined by the presence of hydrogen in their envelope, are thought to occur in the core collapse of massive giant stars and are much less luminous sources of such lines, because the bulk of the ^{56}Ni core, that is formed by explosive burning, collapses to form a neutron star and only a small amount (typically $< 0.1M_\odot$) is ejected; furthermore the gamma rays from its decay are obscured for a much longer time by the massive (typically $> 10M_\odot$) overlying envelope.

The most intense gamma ray lines (with branching ratios) are those from ^{56}Co$\rightarrow$^{56}Fe decay (Huo et al. 1987) at 0.8468 MeV (99.9%), 1.2383 MeV (68.4%), 2.5985 MeV (17.4%), 1.7714 MeV (15.5%), and 1.0378 MeV (14.1%). The ^{56}Co results from the decay of ^{56}Ni which is the parent nucleus produced in supernovae. ^{56}Co decays (Huo et al. 1987) with a mean life of 111.3 days, on a time scale comparable to that required for the supernova ejecta to become transparent to the gamma rays. The decay of ^{56}Ni also gives important gamma ray lines, 0.1584 MeV (98.8%), 0.8119 MeV (86.0%), 0.7500 MeV (49.5%), 0.2695 MeV (36.5%) and 0.4804 MeV (36.5%), but its much shorter mean life of 8.8 days allows the lines to be detectable for a shorter period of time only in the most rapidly expanding and least massive supernovae. Another important radioisotope is ^{57}Co, resulting from the decay of ^{57}Ni produced by neutron capture onto ^{56}Ni. ^{57}Co decays with a longer mean life of 392 days, emitting two major lines (Burrows and Bhat 1986) at 0.1221 MeV (85.9%) and 0.1365 MeV (10.3%), which can be used to study the neutron flux during nucleosynthesis (Clayton 1974).

The principal lines from ^{56}Co and ^{57}Co have been observed from the Type II supernova 1987A in the nearby Large Magellanic Cloud, and these gamma ray line observations have already provided important information on the nucleosynthetic yield and dynamics of that Type II supernova, as we discuss below. Similar observations of gamma ray lines from extragalactic Type Ia supernovae by spectrometers on the CGRO and the planned INTEGRAL (Winkler 1994) should provide critical tests of current models of the nucleosynthetic yield and dynamics of these supernovae. The detection with COMPTEL of the ^{56}Co lines from the Type Ia supernova SN1991T in NGC4527 at a distance of about 13 Mpc has recently been reported (Dan Morris, oral presentation, 17 Texas Symposium, 1994). The expected fluxes of the principal lines from ^{56}Co decay are such that they should be detectable (Chan and Lingenfelter 1991) with INTEGRAL from roughly half of the Type Ia supernovae in the Virgo Cluster. The calculations of the gamma ray line profiles have also indicated how sensitive the line shapes are to the mass-velocity distribution in the

supernova ejecta. Thus, future gamma ray line measurements will be used as tests of supernova models and as diagnostics of supernova structure.

3.1 The Type II Supernova 1987A

The occurrence of the Type II supernova 1987A in the Large Magellanic Cloud, at a distance of about 50 kpc from the Earth, the brightest supernova seen in nearly 400 years, has given us an unprecedented opportunity to directly study supernovae through their gamma ray emission. This supernova explosion occurred (Arnett et al. 1989) in the star Sk -69 202, a B3 I supergiant with a mass of about $16M_\odot$ at the time of the explosion. This supernova has been studied over the full spectrum from radio to gamma rays, and extensive observations of the time dependent gamma ray line intensities and profiles have been made with a variety of spectrometers on balloons and spacecraft (e.g. Matz et al. 1988; Tueller et al. 1990). Comparisons of these observations with predicted line intensities as a function of time (Chan and Lingenfelter 1987; Gehrels, MacCallum and Leventhal 1987; Bussard, Burrows and The 1989) have confirmed the production $0.075M_\odot$ of nucleosynthetic ^{56}Co which has been independently derived from the bolometric luminosity (Arnett et al. 1989).

The gamma ray observations have also shown that the ^{56}Co is extensively mixed in the ejecta. Early calculations (Chan and Lingenfelter 1987) of the gamma ray line emission expected from existing models (Weaver and Woosley 1980a,b) of supernovae in a $15M_\odot$ star suggested that the line emission from ^{56}Co decay would not be visible until nearly 600 days after the explosion if the ^{56}Co was confined to the innermost layers of the supernova ejecta. The subsequent detection (Matz et al. 1988) of the ^{56}Co lines at 0.847 and 1.238 MeV within 200 days after the explosion showed that substantial mixing had occurred in the ejecta (Chan and Lingenfelter 1988; Gehrels et al. 1988), raising the ^{56}Co to high levels in the ejecta where the obscuration by overlying matter was much lower. This has led to extensive modifications of the supernova models to explore the causes and effects of mixing on both the explosive nucleosynthesis and the ejecta dynamics (e.g. Nomoto et al. 1988; Pinto and Woosley 1988; Bussard et al. 1989).

The measured 0.847 and 1.238 MeV line fluxes (Tueller et al. 1990) after the supernova explosion have been compared (see Fig. 9) with calculations (Pinto and Woosley 1988) for the mixed model 10HMM, yielding a reasonably good fit. This model is for a $16M_\odot$ star, having a $6M_\odot$ helium core and $10M_\odot$ blue supergiant envelope, which explodes ejecting the matter above the silicon shell and explosively synthesizes the 0.075 $M_\odot$ of ^{56}Ni that is required to account for the bolometric light curve. In this model the ^{56}Ni has been mixed out through the helium core into the envelope in order to account for the early gamma ray line observations. However, as can be seen in Fig. 9, there is still a significant difference between expected model and the observed profile of the 0.847 MeV line measured 613 days after the explosion, suggesting that even more extensive mixing and asymmetric ejection are required to account for the observed line shape, because the line predicted for the 10HMM model is much too narrow, and too blueshifted to be an acceptable fit. Clearly further study is needed of the dynamics of the mixed and asymmetric ejecta in Type II supernovae.

The 0.122 MeV line from the decay of ^{57}Co, resulting from neutron capture on freshly synthesized ^{56}Ni, has been detected with OSSE (Kurfess et al. 1992). The observed flux of about 10^{-4} photons cm^{-2} s^{-1} suggests that the production ratio of ^{57}Ni/^{56}Ni is about 1.5

times the solar abundance ratio of ^{57}Fe/^{56}Fe. This is quite consistent with current model calculations (e.g. Thielemann, Hashimoto and Nomoto 1990).

3.2 ^{44}Ti Decay Lines From Cas A and Other Young Supernovae

On a longer time scale, ^{44}Ti decays with a mean life of anywhere between 78 years (Frekers et al. 1983) and 96 years (Alburger and Harbottle 1990) to ^{44}Sc, producing gamma ray lines (Lederer and Shirley 1978) at 67.9(100%) and 78.4 keV (98%); ^{44}Sc subsequently decays with a 5.7 hr meanlife to ^{44}Ca, producing a line at 1.157 MeV (100%). The relatively long lifetime of ^{44}Ti, together with its lower nucleosynthetic yield, make these lines too weak to observe from extragalactic supernovae using current detectors. However, this longer life should allow us to observe these lines from Galactic supernovae for several hundred years after the explosion and thus use them to discover the most recent supernovae in our Galaxy. Historical records have allowed us to identify only 2 or 3 nearby Galactic supernovae within the past 300 years. However, the estimated (van den Bergh and Tammann 1991) Galactic supernova rate of $8.4h^2$ per 100 years, gives an expected number of between 6 and 24 Galactic supernovae within the last 300 years assuming $0.5 < h < 1$, or $50 < H_o < 100$ km s^{-1} Mpc^{-1}. The detection of the ^{44}Ti decay lines thus can enable us to discover the locations of all of these other recent supernovae, which were optically obscured, and from their gamma ray locations we can then look in radio and other bands to identify their remnants.

Line emission at 1.157 MeV has recently been measured (Iyudin et al. 1994) with COMPTEL from the youngest known Galactic supernova remnant, Cas A (see Fig. 10). At an estimated (Ilovaisky and Lequeux 1972) distance of 2.8 kpc and estimated (Fesen and Becker 1991) age of ~ 310 yr, the observed ^{44}Sc line flux of $(7.0 \pm 1.7) \times 10^{-5}$ photons cm^{-2} s^{-1} corresponds to an initial ^{44}Ti mass of about 1.4 to $3.2 \times 10^{-4} M_\odot$, given the present uncertainty in the ^{44}Ti meanlife. Such a yield is quite consistent with that expected from current models of Cas A as a Type Ib supernova from the core-collapse of a $\sim 20 M_\odot$ Wolf Rayet star (Ensman and Woosley 1988, Shigeyama et al. 1990).

Assuming a comparable ^{44}Ti yield in the much more frequent Type II supernovae, COMPTEL may be able to locate several other younger but more distant Type II supernovae, and the planned INTEGRAL should discover the most recent dozen or two in our Galaxy.

3.3 Gamma Ray Line Emission From ^{26}Al Decay

On a much longer time scale, gamma ray line radiation at 1.809 MeV results from the decay of ^{26}Al (mean life 1.07×10^6 years) into the first excited states of ^{26}Mg. Because of this long lifetime and an encouraging theoretical ^{26}Al yield in supernovae (Schramm 1971), we proposed (Ramaty and Lingenfelter 1977) that this line should be the nucleosynthetic line with the best prospects for detection. The same idea was also independently proposed (Arnett 1977). The long lifetime is important for at least three reasons: it allows the accumulation of ^{26}Al in the interstellar medium, thereby ensuring steady line emission; it allows the escape of the nucleosynthetic ^{26}Al from its production site before it decays, independent of the complications introduced by the dynamics of the region in which the explosive nucleosynthesis takes place; and it guarantees that the width of the line is going to be very narrow. Gamma ray lines from shorter lived isotopes, such as the 0.847 MeV

line of ^{56}Co (mean life 111 days), can be observed from a relatively close source (e.g. supernova 1987A) only for a short period of time and they are significantly broadened due to the rapid expansion of the supernova envelope. The 1.809 MeV line, on the other hand, is broadened only by the rotation of the interstellar gas, and it is therefore very narrow (full width at half maximum about 3 keV). A narrow intrinsic line width offers considerable advantages for detection with a high resolution Ge instrument. It was because of these considerations that in 1977, two years before the launch of HEAO-3, we proposed that the 1.809 MeV line should be detectable.

The 1.809 MeV line was indeed the first nucleosynthetic gamma ray line to be observed, showing that nucleosynthesis is an ongoing process in the Galaxy at the present epoch. The 1.809 MeV line was first detected (Mahoney et al. 1984) from the direction of the Galactic center with the HEAO-3 high resolution Ge spectrometer and was subsequently confirmed by observations (Share et al. 1985) with the NaI detector on SMM, and balloon borne Ge instruments (e.g. MacCallum et al. 1987). Most recently, imaging observations (Diehl et al. 1994, 1995) of the 1.809 MeV line have been carried out with COMPTEL. As can be seen in Fig. 11, the COMPTEL data reveal a broad, patchy longitude distribution, that is very different from that of the 0.511 MeV line which is strongly peaked at the Galactic center (§4). This result clearly demonstrates that the two line emissions have quite different origins.

Estimates (Mahoney et al. 1984; Skibo, Ramaty and Leventhal 1992) of the total amount of ^{26}Al that resides in the Galaxy range from about 1.7 to $3M_\odot$, depending on assumed model for the Galactic distribution of ^{26}Al, the distance to the Galactic center and the exact values of the 1.809 MeV line fluxes implied by the observations. It should be emphasized that the derivation of a photon flux from data obtained by wide field of view detectors such as SMM and HEAO-3 does depend on the assumed longitude and latitude distribution of the 1.809 MeV line emission.

Although the requirement of 1.7 to 3 $M_\odot$ of ^{26}Al exceeds the originally predicted (Ramaty and Lingenfelter 1977) yield from supernovae, recent increases in the estimates of supernova yields of ^{26}Al and of the present rate of Type II supernova occurrence now suggest that such supernovae could in fact produce ^{26}Al at close to the observed rate. In particular, revisions (Woosley and Weaver 1986) of the reaction rates in core collapse models have substantially increased the calculated yield of ^{26}Al to $\sim 6.9 \times 10^{-5} M_\odot$ in the ejecta of a Type II supernova. More recent studies (Woosley et al. 1990) of hitherto neglected neutrino induced nucleosynthesis suggest a further doubling of the yield of ^{26}Al in such supernovae. Such a yield combined with the higher recent estimate (van den Bergh and Tammann 1991) of the Galactic Type II supernova rate of $6.1h^2$ per 100 years, gives an expected Galactic nucleosynthesis rate of $(4-8)h^2 M_\odot$ of ^{26}Al per 10^6 years. Thus Type II supernovae alone could account for all of the observed Galactic ^{26}Al production for any $h > 0.5$, or $H_o > 50$ km s^{-1} Mpc^{-1}. The calculated ^{26}Al yields for Type I and other supernovae are negligible by comparison (Nomoto, Thielemann and Yokoi 1984). Other possible sources are novae and Wolf-Rayet stars. However, recent calculations attribute no more than $0.5M_\odot$ of ^{26}Al per 10^6 years to Galactic novae (Prantzos 1991), and $0.2-0.3M_\odot$ per 10^6 years to Wolf-Rayet stars (Paulus and Forestini 1991). These objects, therefore, appear to produce less than 1/2 of the ^{26}Al required to account for the observations.

Moreover, the COMPTEL maps of the 1.809 MeV line intensity show an enhancement at the Vela supernova remnant (Fig. 11), supporting a supernova origin of the ^{26}Al, and not at γ Vel which would have been expected if Wolf Rayet stars were the source.

In addition to the Galactic longitude and latitude distribution of the 1.809 MeV line emission, information on the origin of the ^{26}Al could also be obtained from studies of the shape of the line. Doppler shifts of the line centroid energy of as much as 0.5 keV are expected due to Galactic rotation, depending on the distribution of the ^{26}Al and the direction of observation (Skibo and Ramaty 1991). All of these studies will allow a much better understanding of the origin of the radioactive Al, and hence of the chemical evolution of the Galaxy.

4. GALACTIC POSITRON ANNIHILATION RADIATION

The 0.511 MeV line is perhaps the most important line in gamma ray astronomy. Its study began in 1970 when a line-like feature around 0.47 MeV, assumed to be due to positron annihilation, was observed from the direction of the Galactic center with a balloon borne NaI detector (Johnson, Harnden, and Haymes 1972). Various schemes were proposed to account for the redshift. Ramaty, Borner and Cohen (1973) suggested that the observed line was due to gravitationally redshifted annihilation radiation produced on the surfaces of neutron stars, while Leventhal (1973) pointed out that the convolution of a spectrum consisting of the 0.511 MeV line and the accompanying positronium continuum with the response function of a detector with poor energy resolution would lead to the apparent redshift. It was not until 1977, that the line energy was accurately determined with a Ge spectrometer (Leventhal, MacCallum, and Stang 1978). The observed line center energy, 510.7 ± 0.5 keV, clearly established that the radiation was due to the annihilation of positrons. In this and all subsequent detections with Ge spectrometers (Riegler et al. 1981; Gehrels et al. 1991; Leventhal et al. 1993; Smith et al. 1993), the line width was found to be very narrow (full width at half maximum < 3 keV) and the line center energy to be at 0.511 MeV within errors less than a keV (Fig. 12). Reviewing the possible origins for the line emission (Ramaty and Lingenfelter 1979), we pointed out that the most likely sources for the positrons responsible for the observed annihilation radiation were the radionuclei ^{56}Co, ^{44}Ti and ^{26}Al resulting from various processes of Galactic nucleosynthesis (see also Clayton 1973).

This point of view, however, was challenged by the subsequent HEAO-3 result, that the 0.511 MeV line flux from the direction of the Galactic center had varied on a time scale shorter than 1/2 year (Riegler et al. 1981). Even though the significance of this result was weakened by a different analysis of the HEAO-3 data (Mahoney, Ling and Wheaton 1994), confirmation for the 0.511 MeV time variability was provided by a series of observations carried out with balloon borne Ge detectors from 1977 through 1984. Whereas strong 0.511 MeV line emission was seen in the 1977 and 1979 flights, only upper limits were obtained in 1981 and 1984. The statistical significance of the implied variability was about 3σ. Since variability on time scales of a few years or less can not be expected if the positrons result from multiple nucleosynthetic events, we proposed that the bulk of the positrons should be produced at or near a single compact object of less than a light year in diameter, most likely a black hole in the Galactic center region (Ramaty, Leiter and Lingenfelter 1981). We subsequently suggested (Lingenfelter and

Ramaty 1982) that the annihilating positrons could be produced by $\gamma\gamma$ pair production of the higher energy ($> m_e c^2$) continuum photons which showed an even greater intensity variation simultaneous with the annihilation radiation. From the observed continuum flux and the estimated (Galactic center) distance to the source, the required rate of pair production limited the size of the source region, less than about 10^9 cm. On the basis of this result, we pointed out that the source probably was a stellar mass black hole that did not necessarily reside at the dynamical center of the Galaxy.

The possibility of positron production near black holes was strengthened by the discovery of a broad line at ~0.4 MeV from the X-ray source 1E1740.7-2942, located at an angular distance of 0.9° from the Galactic center (Bouchet et al. 1991; Sunyaev et al. 1991; see also Gilfanov et al. 1994). This transient line emission was observed on 13–14 October 1990 with the imaging gamma ray spectrometer SIGMA. Similar line emission from an unidentified source or sources in the direction of the Galactic center was also observed with non imaging Ge detectors flown on balloons in 1977 (Leventhal et al. 1978; Leventhal and MacCallum 1980) and 1989 (Smith et al. 1993), as well as from another unidentified source 12° away from the Galactic center with HEAO-1 (Briggs et al. 1995). We discuss these further in §5. If these 0.4 MeV line features are due to gravitationally redshifted positron annihilation produced near black holes, it is reasonable to assume that a fraction of the positrons could escape and annihilate at large distances from the hole to produce a line at precisely 0.511 MeV (Ramaty et al. 1992). If the pair production near the hole is time variable, the 0.511 MeV line flux will also vary in time, although the time scale of the latter variability would depend on the density of the medium in which the positrons annihilate, $\sim 10^5/n(\mathrm{cm}^{-3})$ yrs (Guessoum, Ramaty, and Lingenfelter 1991).

Numerous observations of 0.511 MeV line emission from the Galactic center and the Galactic plane were carried out with OSSE on CGRO. This observatory was launched in 1991, and there are published 0.511 MeV line observations from July 1991 to October 1992 (Purcell et al. 1993). OSSE is a non-imaging NaI instrument with a relatively small field of view ($11^\circ.4 \times 3^\circ.8$). Most of the OSSE observations were carried out with the detector pointing at or close to the Galactic center. These observations suggest that the 0.511 MeV line emission is strongly concentrated toward the Galactic center. None of the OSSE observations show significant time variability, but they allow 3σ limits on weekly variations of $\pm 60\%$ and daily variations of $\pm 120\%$ relative to the observed flux of $(2.5 \pm 0.3) \times 10^{-4}$ photons cm^{-2} s^{-1}. Thus the question of the variability of the 0.511 MeV line flux must await future observations.

Models for the 3 dimensional Galactic distribution of annihilation radiation based on the OSSE and other 0.511 MeV line observations have been developed (Skibo 1993; Ramaty, Skibo and Lingenfelter 1994). The calculated longitude distributions (integrated over all Galactic latitudes) for two of the models are shown in Fig. 13. The dashed curve is based on the nova distribution of Higdon and Fowler (1989) which consists of two morphological parts, a disk and a spheroid centered at the Galactic center. Because novae occur on accreting white dwarfs that eventually become Type Ia supernovae, and because such supernovae could be important positron sources, this distribution should provide a reasonable starting point for the analysis. But as demonstrated by Skibo (1993) and Ramaty, Skibo and Lingenfelter (1994), this distribution cannot account for the very strong

concentration of the 0.511 MeV line emission at the Galactic center (P$\sim 10^{-6}$, Skibo 1993). The solid curve was obtained by adding to the nova distribution an additional spheroid, which, for simplicity was assumed to have the same shape as the spheroid associated with the nova distribution itself. We refer to the nova part and the additional spheroidal part of the total distribution as the Galactic plane and the central Galactic components, respectively. By allowing the ratio of positron production in these two components to vary, a good fit to the data was obtained (P$\sim$0.6, Skibo 1993) for a central Galactic–to–Galactic plane positron production ratio of 2.6. Normalization to the 0.511 MeV line observations also determines the absolute productions, 2.6×10^{43} e$^+$ s^{-1} and 1×10^{43} e$^+$ s^{-1}, for the two components respectively.

The bulk of the positrons responsible for the Galactic plane component could result from the decay of ^{56}Co, ^{44}Sc and ^{26}Al produced in various Galactic processes of nucleosynthesis (e.g. Lingenfelter, Chan and Ramaty 1993). The contribution of other processes (e.g. cosmic ray interactions, pair production in pulsars) is quite small (Ramaty and Lingenfelter 1991). The total Galactic positron production rate from the decay of ^{26}Al was estimated (Skibo et al. 1992) to be about 0.2×10^{43} positrons s^{-1} (see also §3), i.e. about 20% the total Galactic plane component. The rest of the positrons probably result from ^{56}Co and ^{44}Sc, where the total production rate of these isotopes scales with the present rate of Galactic iron nucleosynthesis and the relative contributions of these two isotopes depends on the positron escape fraction from the envelopes of Type Ia supernovae (Chan and Lingenfelter 1993). These two radionuclei are thought to be produced primarily in Type Ia supernovae and the distribution of their production rate is expected to follow that of Galactic novae.

The origin of the positrons in the central component is essentially unknown. It is possible that black hole candidates are a major contributor to positron production in the Galactic center region at the present epoch. Because both the positron annihilation time and the distance that the positrons can travel from their sources to their annihilation site is strongly dependent on the properties of the medium in which they are trapped, both the spatial extent of annihilation radiation produced by a point source of positrons and the time dependence of the emission are highly uncertain. It is possible that the entire central Galactic component is fed by just 1E1740.7-2942. But additional sources may also contribute significantly (see Ramaty and Lingenfelter 1994 for more details). We might expect comparable enhancements of the 0.511 MeV emission in the direction of Nova Muscae and other candidate black hole sources, although the production of a narrow 0.511 MeV line depends on the existence of not only a positron source but also a sufficiently dense annihilation site. Clearly much better mapping of the Galactic annihilation radiation by the planned INTEGRAL and perhaps other missions is needed to resolve the question of its origin.

5. LINE FEATURES FROM BLACK HOLE CANDIDATES

As mentioned above, line-like emission features at $\sim$0.4 MeV have been observed from a number of sources assumed to be accreting black holes, and in several of these observations this line was accompanied by another line at $\sim$0.2 MeV. Line emission at both $\sim$0.48 MeV and $\sim$0.19 MeV were simultaneously observed with SIGMA from Nova Muscae during its outburst on 20 January 1991 (Goldwurm et al. 1992). Similar features

at 0.496 MeV and ~0.17 MeV and at ~0.40 MeV and ~0.16 MeV were observed with balloon-borne Ge spectrometers from an unidentified source, or sources, in the Galactic center region in 1977 (Leventhal and MacCallum 1980) and 1989 (Smith et al. 1993), respectively. Only the higher energy line at ~0.40 MeV was observed with SIGMA from 1E1740.7-2942 during an outburst on 13–14 October 1990 (Bouchet et al. 1991; Gilfanov et al. 1994), and at ~ 0.46 MeV with HEAO-1 from another source, possibly the low mass X-ray binary 1H1822–371, about 12° away from the Galactic center (Briggs et al. 1995). Two other transients exhibiting emission features were observed with SIGMA from 1E1740.7-2942 (Cordier et al. 1993; Gilfanov et al. 1994). However, for one of these, that on 19-20 January 1992, the flux reported by SIGMA is in conflict at more than 3σ with co-temporal CGRO OSSE and BATSE observations (Jung et al. 1995; Smith et al. 1995).

The ~0.4 MeV line has frequently been assumed to be redshifted positron annihilation radiation. If the redshift is gravitational, the line must be formed around a compact object, presumably an accreting black hole, at distances varying from a few Schwarzschild radii for the 1E1740.7-2942 source, to more than 10 Schwarzschild radii for the 1977 source and Nova Muscae. The ~0.2 MeV line, observed at the same time from the latter two sources, can been interpreted as Compton backscattered reflection of the annihilation feature from the inner edge of an optically thick accretion disk (Lingenfelter and Hua 1991; Hua and Lingenfelter 1993).

This second line results from the fact that Compton scattering of photons of energy E_0 into an angle θ will produce photons of energy

$$E_s = \frac{E_0}{1 + \frac{E_0}{m_e c^2}(1 - \cos\theta)}, \tag{5}$$

so that, if the initial photons form a line at $E_0 \simeq m_e c^2$, then backscattered photons ($\cos\theta$=–1) will form another line at $E_s \simeq m_e c^2/3 = 0.17$ MeV. The intensity of the backscattered line is typically only ~ 5% of that of the initial line, while the observed ratio of these lines is about 30% for Nova Muscae. However, the initial line can be strongly attenuated by the accretion disk itself. Hua and Lingenfelter (1993) have shown that such scattering gives excellent agreement with the observed pairs of line-like features which were seen from both Nova Muscae (Fig. 14) and the 1977 source (Lingenfelter and Hua 1991). Moreover, assuming that the observing angle of 68±14° relative to the axis of the accretion disk, determined for Compton scattering in Nova Muscae, is the same as the inclination angle of the binary system, a central black hole mass of 5.6±1.3 $M_\odot$ can be determined using the optically determined mass function (Remillard, McClintock, and Bailyn 1992). However, the temperature kT of the gas which backscatters the photons should not exceed about 10 keV since otherwise the backscattered feature will be broader than observed.

On the other hand, for the 1E1740.7-2942, 1989 and 1H1822–371 sources, the higher energy lines were observed at energies implying much larger redshifts. This would imply that pair production and annihilation occur at essentially the same physical site, which leads to a problem because the temperature required to produce the pairs greatly exceeds the upper limit on the temperature set by the width of the ~0.4 MeV line. This argument has been quantified by Maciolek-Niedzwiecky and Zdziarski (1994) who showed that the

line centroid requires that the positrons annihilate in a region around 3 Schwarzschild radii from the hole and that the line width requires that the temperature in this region be ($kT \lesssim$ 50 keV).

A different explanation of the redshift, assuming positron annihilation, is that the observed ~0.4 MeV line energy is due to the motion of the annihilating region (Misra and Melia 1993) where the pairs annihilate at the base of a jet emanating from the black hole. This explanation would allow the separation of the annihilation region from the pair production region. While this scenario could provide an explanation for the 1E1740.7-2942 observation, which revealed only the higher energy line, it might not explain the 1989 data, for which the lower energy line was more intense than that at higher energies; is not clear whether the annihilation line could be greatly attenuated relative to the backscattered line in such a jet geometry.

An alternative interpretation (Skibo et al. 1994) for both the ~0.2 and ~0.4 MeV line features is that they result form Compton scattering of high energy continuum photons in a jet. This can again be seen from Eq. (5). If $E_0 >> m_e c^2$, then $E_s \simeq m_e c^2/(1-cos\theta)$, i.e. energy of the scattered photon is independent of its initial energy and depends only on the scattering angle. Consequently, if the original spectrum were very flat, or consisted entirely of photons well above $m_e c^2$, the scattered photons would accumulate at E_s, producing a line-like feature. Skibo et al. (1994) showed that such Compton scattering in a double sided jet can produce the two lines around 0.4 and 0.2 MeV for jet bulk flow velocities β around 0.55 and observing angle cosines in the range 0.2 to 0.6. The required observing angle for Nova Muscae for this model is 68° (J.G. Skibo, private communication 1994), essentially the same as that for the backscatter model, so that the implied black hole mass is nearly identical. Also radio observations show that 1E1740.7-2942 is in fact associated with a double sided jet (Mirabel et al. 1992).

Lastly, a broad line in the 0.4–0.5 MeV can also be produced by interactions amongst α particles, ^{4}He$(\alpha,p)^7$Li^{*478} and ^{4}He$(\alpha,n)^7$He^{*429} (Kozlovsky and Ramaty 1974). This feature has been seen from solar flares (§2). However, the expected line centroid, without any redshift, is at 0.45 MeV and this is in marginal conflict with the Nova Muscae observation, for which the line centroid was at 0.48 ± 0.02 MeV (Goldwurm et al. 1992), and definitely with the 1977 observation for which the line centroid was at 0.496 MeV. On the other hand, the observations (Martin et al. 1992; 1994) of high lithium abundances in the binary companions of the black hole candidates V404 Cygni, Cen X-4 and A0620, possibly due to α–α reactions in the accretion disks of the holes, do provide support for this model. Again Compton backscattering of these α–α photons from the inner region of an optically thick accretion disk could account for the $\lesssim$0.2 MeV line emission.

Fortunately, there are tests to distinguish between the various models. The principal prediction of the annihilation/backscattering model is that the two lines should always be just below 0.511 MeV and around 0.2 MeV for all sources. This seems to be borne out by the current, albeit very limited, source population. On the contrary, the jet model in which both line are due to Compton scattering, does predict lines at various energies, including energies above 0.511 MeV. The observation of a broad line around 1 MeV from Cygnus X-1 (Ling and Wheaton 1989) may be due Compton scattering of high energy photons into viewing angles close to the forward direction. Polarization observations could

also distinguish the models. For Compton scattering in jets, both lines should be polarized (see Skibo et al. 1994); however, no polarization is expected in either of these lines for the annihilation/backscattering model. (Unpolarized radiation undergoing Compton scattering becomes polarized, except in the backward direction.) The required polarization observations have not yet been carried out.

The α–α interaction model makes two important predictions. The first one concerns the isotopic ratio ^{7}Li/^{6}Li in the binary companions of the black hole candidates. A ratio around 1.5 would favor the α–α reactions; a significantly higher ratio would probably require another mechanism for producing the Li. The second one involves the very narrow delayed 0.478 MeV line from ^{7}Be decay. For an outburst similar to that of Nova Muscae on 20 January 1991, we expect a delayed flux of $\sim 4{\times}10^{-6}$ photons cm^{-2} s^{-1}, equal to the ratio of ^{7}Be to ^{7}Li production of ~ 1 (Ramaty et al. 1979) times the 10.4% branching ratio times the observed broad line flux of $6{\times}10^{-3}$ photons/cm^{2}sec times its 0.5 day duration divided by the 77 day ^{7}Be meanlife. Such a narrow line flux could be detected by the planned INTEGRAL spectrometer.

6. CONCLUSIONS

As we have seen, the study of gamma ray line radiation indeed spans a broad range of astrophysical problems. In solar flares the line radiation addresses problems of particle acceleration and transport, particle trapping, magnetic field structure, plasma turbulence and solar atmospheric composition. Of all astrophysical sites, the richest gamma ray line spectra observed so far are those from the Sun.

Deexcitation gamma ray line emission has been observed from the Orion star formation region showing that the gas and dust in this molecular cloud complex are currently undergoing strong irradiation by low energy cosmic rays. Given that the duration of the irradiation is about 10^5 years, the time span since a possible recent supernova in Orion, the total energy in accelerated particles is about 10^{51} erg. The relationship of such irradiation to the question of the origin of the light elements is currently under investigation. However, neither the overall Galactic ^{26}Al nor the ^{26}Al that was present at the formation of the solar system could have originated in accelerated particle bombardment.

Gamma ray lines from processes of nucleosynthesis have been observed from a variety of sites. Observations of the ^{56}Co lines from supernova 1987A have shown that the supernova explosion is much more complex than previously thought. Specifically, the early appearance of the lines requires mixing, while the shapes of the lines, determined with a high resolution spectrometer, require asymmetric supernova ejecta. Recently, gamma ray line emission from ^{44}Ti decay has been observed from Cas A, opening the possibility of observing similar line emission from other young, and hitherto unknown, supernova remnants in our Galaxy. The 1.809 MeV line from ^{26}Al decay has been observed and imaged. The bulk of the 2 $M_\odot$ of ^{26}Al in the interstellar medium are thought to be due to Type II supernovae which exploded in the Galaxy in the last million years. A supernova origin is supported by the observation of enhanced 1.809 MeV line emission from the Vela supernova remnant.

Galactic annihilation radiation has been observed. The high resolution Ge detectors flown on balloons have shown that there is strong, very narrow line emission produced at precisely 0.511 MeV at or near the Galactic center. The recent OSSE mapping of the

flux in this line has shown that there is much emission strongly concentrated within less than a few degrees from the Galactic center. We believe that this concentration points to a black hole origin, specifically pair production in photon-photon collisions near the hole and escape and annihilation of the positrons in the surrounding medium. In addition, observations of the diffuse Galactic annihilation radiation set important constraints on the current rate of iron nucleosynthesis in the Galaxy.

Transient emission lines from black hole candidates have been discovered. Such lines were seen from 1E1740.7-2942 during an outburst in 1990, from Nova Muscae during an outburst in 1991, and from several other unidentified sources. The interpretations involve redshifted pair annihilation, Compton backscattering, Compton downscattering of collimated high energy gamma ray continuum and possibly α–α interactions producing ^{7}Li and ^{7}Be. The various models make predictions that will be tested by future observations. Because of their low duty cycle, these transients can be best studied by continuously monitoring the Galactic plane with wide field of view gamma ray spectrometers. These lines are providing unique probes of the accretion disks and jets of black holes.

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FIGURE CAPTIONS

Fig. 1. Calculated gamma ray deexcitation spectra; upper panel – a combined narrow and broad line spectrum; lower panel – a broad line spectrum showing the very narrow lines from long lived radionuclei (from Ramaty 1995).

Fig. 2. A theoretical solar flare gamma ray spectrum showing the strongest expected nuclear deexcitation lines.

Fig. 3. Observed solar flare gamma ray line spectrum fitted with theoretical curve (from Murphy et al. 1991).

Fig. 4. The observed location of the nuclear line emission in the Orion star formation region and the spectrum of the line emission (from Bloemen et al. 1994).

Fig. 5. Calculated energy deposition rates in Orion by accelerated particles of various compositions in a neutral ambient medium with solar photospheric composition, as functions of the accelerated particle spectral parameter E_0 (from Ramaty et al. 1995b).

Fig. 6. Production ratios of ^{9}Be to 3-7MeV nuclear deexcitation photons for various accelerated particle compositions as functions of the accelerated particle spectral parameter E_0 (from Ramaty et al. 1995b).

Fig. 7. Production ratios of ^{7}Li to ^{6}Li for various accelerated particle compositions as functions of the accelerated particle spectral parameter E_0. Shown are the meteoritic ratio (Anders & Grevesse 1989) and the two values for clouds in the direction of ζ oph (Lemoine et al. 1995).

Fig. 8. Production ratios of ^{26}Al to ^{9}Be for various accelerated particle compositions as functions of the accelerated particle spectral parameter E_0 (from Ramaty et al. 1995b). The horizontal bar represents the protosolar ^{26}Al abundance and the probable E_0 range.

Fig. 9. The 0.847 MeV line observed (Tueller et al. 1988) with a high resolution detector from Supernova 1987A compared with calculations (Pinto and Woosley 1988) for the mixed model 10HMM, suggesting significant asymmetry in the ejecta.

Fig. 10. The ^{44}Ti line emission from the young supernova remnant Cas A; left panel – the location of the line emission; right panel – the spectrum of the line emission (from Iyudin et al. 1994).

Fig. 11. The sky in 1.809 MeV ^{26}Al decay line emission (from Diehl et al. 1995).

Fig. 12. The 0.511 MeV positron annihilation line observations from the region of the Galactic center (from Leventhal et al. 1993).

Fig. 13. Galactic longitude profiles of the 0.511 MeV line emission (from Skibo et al. 1993).

Fig. 14. The observed (Goldwurm et al. 1992) spectrum from Nova Muscae during the outburst on 20 January 1991 compared with the Monte Carlo simulated (Hua and Lingenfelter 1993) spectrum of Compton scattered annihilation radiation for an accretion disk around a black hole, superimposed on a background power law with index $s = -2.90$ and viewed at an observing angle of 68° with respect to the axis of the accretion disk.